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STATUS OF THE LOS ALAMOS TRITIUM BETA DECAY EXPERIMENT

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ABSTRACT

The Los Alamos tritium experiment employs a gaseous tritium source and a magnetic spectrometer to determine the mass of the electron antineutrino from the shape of the tritium beta spectrum. Since publication of the first result from this apparatus ($m_{\nu} < 27$ eV at 95% confidence), work has concentrated on improving the data rates. A 96-element Si microstrip array detector has been installed to replace the single proportional counter at the spectrometer focus, resulting in greatly increased efficiency. Measurements of the 1s photoionization spectrum of Kr now obviate the need for reliance on the theoretical shakeup and shakeoff spectrum of Kr in determining the spectrometer resolution.

I. INTRODUCTION

It is now generally recognized that measurement of the electron antineutrino mass in tritium beta decay, while the most sensitive direct technique known, may be subject to a variety of systematic errors. Detailed understanding and careful control of these effects is essential if correct results are to be obtained. Generally speaking, neutrino mass causes a distortion of the beta spectrum that is strongly correlated with resolution-like contributions. An overestimate of any of the sources of instrumental width will lead to an overestimate of the neutrino mass (and conversely), without there being necessarily any loss of quality of fit to the data.

The sources of resolution broadening can be grouped into three classes: 1) spectrometer optical width, 2) energy loss and backscattering in the source material, and 3) the final-state spectrum of the daughter molecular ion remaining after a tritium atom has decayed. While a variety of experimental tests can be brought to bear on the first two, theory is the sole source of information about the third. For this reason, experiments that make use of simple sources (nuclear, atomic or molecular tritium) are now receiving close attention, since the theory is more tractable and reliable.

The Los Alamos tritium experiment[1] makes use of a gaseous source of molecular T_2 to take advantage of the comprehensive theoretical understanding[2-5] of the quantum mechanics of 2-electron systems. In addition, the source is thin (minimizing scattering corrections) and there is no backscattering. Initial data taken as a proof-of-principle yielded[1] an upper limit to the mass of the electron antineutrino of 27 eV at 95% confidence level. The precision of the result was limited primarily by statistics, and was not sufficient to discriminate between two earlier results obtained with solid sources (ITEP[6], $m_\nu = 26(5)$ eV; Zürich[7], $m_\nu < 18$ eV).

Sensitivity to neutrino mass increases extremely slowly with data acquisition time, roughly as the fifth root, so it was clearly necessary to improve the data rate in the Los Alamos experiment dramatically in order to reach the goal of 10 eV mass sensitivity. The upgrade has been completed successfully, as is described below, and a number of ancillary improvements and measurements have also been carried out.

II. NEW DETECTOR FOR SPECTROMETER

The gaseous source and spectrometer have been described previously.[8,9] For present purposes we only draw the reader's attention to the detector at the focus of the spectrometer. For the 1987 data this detector was a cylindrical single-wire proportional counter having a window of 400 $\mu g/cm^2$ of Mylar and an annular slit 2 mm wide and 2 cm in diameter to define the momentum acceptance. The energy resolution for 26-keV electrons was 20% and the position resolution 6 mm FWHM (position resolution was used to reject backgrounds from events not close to the slit). This detector was simple and serviceable, but data could be taken only one momentum point at a time.

The new detector is an octagonal array of 300-μm planar passivated Si wafers (n-type) each with a sensitive area of 7 x 10 mm^2. The sensitive area is subdivided into 12 strips on 0.83-mm centers by readout pads. There are thus 96 microstrips tiling the surface of (approximately) a 2-cm diameter cylinder. A figure showing the arrangement may be found in Ref. 9. The wafers, manufactured by Hamamatsu Photonics KK, are mounted on 1-mm thick sapphire substrates (Saphikon Inc.) clamped at one end to water-cooled copper braids. Sapphire is not only an excellent conductor of heat (there are thermal radiation loads from the nearby spectrometer conductors) but is also quite radiopure. The wafers are water-cooled to 13 C; further cooling was considered unwise in view of the possible pumping of tritiated condensate onto the surfaces of the detectors. For electron spectroscopy, the customary Au layer on the entry surface of the wafers has been omitted and only the thin (less than 0.5 μm) ion-implanted contact intervenes. While this leads to a higher-resistance contact than would be desirable in timing applications, there is no penalty in resolution. For 23-keV electrons, resolutions of 2.5 to 4.0 keV FWHM are observed.

The wafers are biased on the outer, common, surface to +70 volts, and the pads are DC-coupled to preamps via flexible Kapton printed ribbons that are sealed through the vacuum wall. Leakage currents, typically 2 nA per strip, are monitored via the preamp output offsets. The preamps are Rel-Labs RL-789 triple hybrid units with 100-MΩ feedback resistors. The preamp signals are each amplified, shaped, and passed through a biased amplifier to remove the noisy baseline before being summed in groups of 12. A multichannel ADC (LeCroy 2259B) records the 8 multiplexed analog signals, and 3 LeCroy 4532 Majority Logic Units register 96-bit patterns describing the locations and multiplicities of the events. Valid events have a multiplicity of one. Events are processed and written on two disks by a 12-MHz computer in 400 μs.

The beta spectrum is formed by setting the spectrometer to analyze a fixed momentum and scanning the accelerating voltage on the source. A typical data acquisition interval at a particular voltage is 30 seconds, at the end of which a 1024-channel spectrum from the Si monitor detector and the contents of scalers used in dead-time correction are written to disk after the event-mode data. After every 5 data points, a calibration measurement at the voltage farthest from the endpoint (i.e. the highest voltage) is taken to monitor stability. Data voltages are repeated with a frequency that reflects the parts of the spectrum most significant in determining the neutrino mass. Including calibration points, a full data set consists of approximately 5700 measurements at 800 voltages.

Analysis of the data begins with manual creation of a set of 96 windows on the energy spectra from the individual pads. The windows include most (typically about 90%) of the counts from 23-keV electrons from the source, and exclude the bulk of the background counts from tritium in the spectrometer. With these windows a data-summary "tape" (disk file) is prepared that contains the total numbers of counts within the windows at each data point.

Each pad receives counts corresponding to a slightly different momentum, the total range being about 100 eV from one end of the detector to the other. A central pad is arbitrarily selected and shift voltages (in multiples of 3 V) added or subtracted to the spectra of other pads to align the centroids of the Kr resolution functions. Relative efficiencies for the pads are also derived at this time from the individual Kr spectra. These relative efficiencies drop out (to an excellent approximation) in the summed spectra except within 100 V of the ends of the spectra, where, because of the shifts, not all pads contribute to each combined spectrum point. A combined tritium beta spectrum is formed based on the shifts, efficiencies, dead-time corrections, and beta-monitor normalizations, and the combined resolution function is formed in the same way from $^{83}Kr^m$ data.

Two tritium data sets were taken in late 1988. Representing about 4 days of data acquisition, each spectrum contains 4700 counts in the last 100 eV, of which 910 are background. The 12 days of data published[5] in 1987 contained 649 counts in the last 100 eV, of which 141 were background. Thus, while the signal-to-background ratio is about the same, the gross data rate near the endpoint is more than 20 times higher. (A factor 3 of this improvement represents the increased time spent near the endpoint, and is thus simply a change in strategy. On the other hand, the spectrometer acceptance was also reduced a factor of 2 to improve the resolution in the most recent data sets.) It will not be possible to give a new result for the neutrino mass until the new software has been thoroughly checked and several small theoretical corrections have been calculated.

III. SHAPE OF THE $^{83}Kr^m$ CONVERSION LINE

The instrumental resolution of the apparatus is measured with the monoenergetic 17820-eV K-conversion line of $^{83}Kr^m$. The line is not in fact truly monoenergetic, but is accompanied by shakeup and shakeoff satellites that result from excitations in the Kr atom's outer shells when a K electron has been ejected. The positions and intensities of the satellites, as well as the natural width of the "diagram" line, must be known in order to extract the instrumental resolution from the data. There being little detailed theoretical or experimental information about the Kr satellite structure, a spectrum was constructed for the 1987 analysis by drawing on a number of different sources.

The relaxed state of the resulting Kr^+ ion is $1s(2s)^2(2p)^6(3s)^2(3p)^6(3d)^{10}(4s)^2(4p)^6$ before the K vacancy is filled. In general, the final configuration will, some of the time, have electrons in excited states, e.g. $(4s)(4p)^6(5s)$. However, the presence of more than 1 excitation at a time (in the primary shakeoff spectrum) is relatively rare.[10]

The levels whose binding we needed are in the Kr^+ ion having a core vacancy. The potential felt by the outer electrons is very closely that of a Rb^+ ion. We therefore used the level spacings[11] for neutral Rb, shifted by 11.8 eV to correspond to the calculation by Carlson and Nestor[12] for the binding of the 4p shell in Kr^+ with a 1s vacancy, 26.1 eV (see Table I).

TABLE I. Binding energies in Kr^+.

Shell (nl2j)	Binding energy (eV)
3p1	259.2
3p3	250.3
3d3	123.6
3d5	122.1
4s	41.1
4p1	26.6
4p3	25.8

Within the framework of the sudden approximation, the satellite spectrum is independent of the energy of the primary ejected electron above a few hundred eV. Carlson and Nestor[12] have calculated the probability that a vacancy will exist in any given shell after ejection of an inner-shell electron. It is evident from their Table III that vacancies are more likely to occur in the outer orbitals, and that the probability of creating such a vacancy increases the deeper the initial hole.

There was very little relevant experimental data. Spears et al.[13] measured photoelectron spectra from the 3p and 3d shells in Kr. The special value of their data is that they identified the location of the state(s) receiving the majority of the shake-up strength. Most of the shake-up goes into a single state (or very close multiplet) at 20.4 eV above the relaxed configuration. This state carries an intensity of 5.5(10) (3p ejection) to 8(1) percent (3d ejection) of the diagram line. For shaking from any given shell, one may safely assume that the relative amounts going to bound and continuum states are largely independent of the location of the primary hole (provided it is deep enough), but that the total shaking probability from any shell varies smoothly, as in Carlson and Nestor's calculation, with the depth of the hole. The prescription for calculating the shake-up intensity was then to take the observed intensity from Spears et al.

for the 3d and 3p photoelectron spectra as having an average value of 7% of the diagram line. The 4p vacancy probability increases by the ratio 13.45/10.14 in going from 3d and 3p to 1s holes.[12] Therefore the 4p shake-up percentage also increases by the same ratio and goes from 6.15% to 8.15%. The difference between that and the 4p vacancy probability, 5.30%, goes into shake-off.

Another useful approximation is that shake-up diminishes rapidly relative to shake-off for shaking of deeper shells. In the words of Carlson et al.[10], "if the electron has enough energy to promote itself from an inner shell to an excited state, it will probably also have the extra amount necessary for going to the continuum." Since the 4p shell contributes most of the shaking strength, about half of which is shake-up, then more deeply bound shells will contribute mostly to the continuum. We neglected shake-up from all shells except the 4p.

Using hydrogenic wavefunctions, Levinger[14] presented closed-form expressions for the kinetic energy distribution for electrons shaken off from the 1s, 2s, and 2p shells. We used the 2p calculation for 4p, and the 2s for 4s shakeoff. While these spectra are probably not very realistic, there is a tendency for their widths to decrease with increasing principal quantum number. Since the distributions were already very narrow in comparison with our instrumental resolution, this uncertainty is not likely to affect the conclusions.

The width of a K vacancy in Kr can be obtained from the compilation of Bambynek et al.[15], who show that K widths have a smooth Z dependence:

$$\Gamma_K = 1.73\ Z^{3.93}\ \mu\text{eV}.$$

For Z = 36 this yields 2.26 eV for the diagram line. It seems self-evident that the width of the shakeup satellites cannot be less than that of the primary 1s conversion line, and we used this value for the shakeup satellite as well.

We collect in Table II the results needed to calculate the full shake spectrum within about 100 eV of the main conversion line. The resulting shake spectrum, as used in the 1987 analysis,[1] is shown in Fig. 1.

The experimentally observed lineshape in the tritium apparatus is the convolution of the above Kr spectrum with an energy-loss spectrum due to scattering in the residual gas, and with the instrumental response, taken to be a skewed Gaussian:

$$P(x) = A \exp\left[\frac{-(x-\mu)^2}{2[\sigma + \lambda(x-\mu)]^2}\right]$$

where A, σ, μ, and λ are parameters. Note that such an expression is incapable of describing a long tail on the resolution function.

TABLE II. Shakeup and shakeoff satellites for Kr K conversion.

Energy (eV)	Intensity (%)	Spectral shape
0.0	79.5	2.26-eV Lorentzian
20.4	8.2	2.26-eV Lorentzian
26.1	5.3	2p Levinger spectrum
41.0	1.8	2s Levinger spectrum
122.8	3.6	2p Levinger spectrum
TOTAL	98.4	

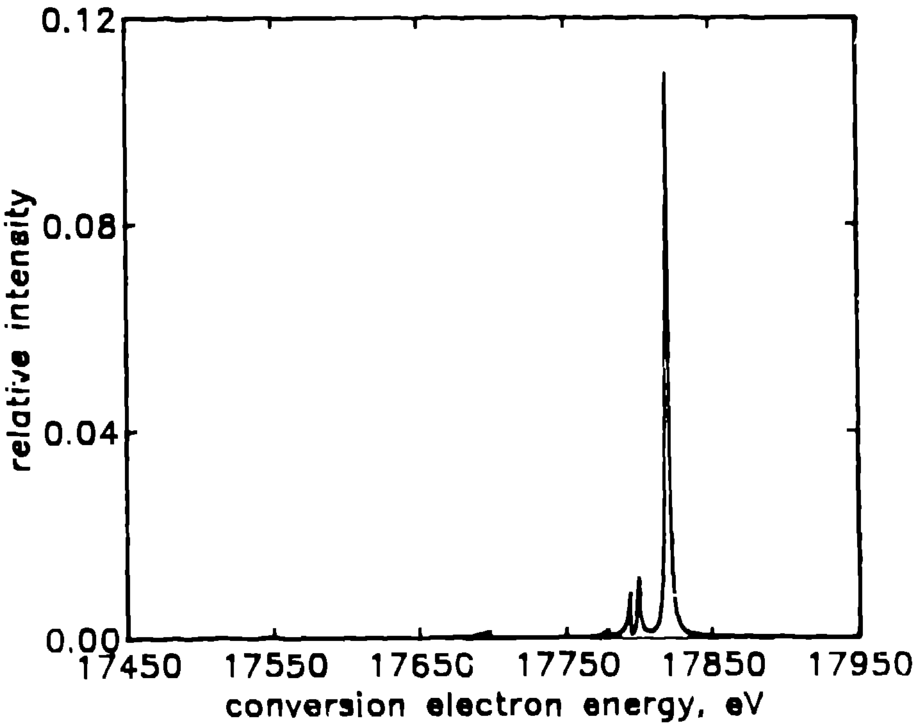

Fig. 1. Calculated shake spectrum for $^{83}Kr^{m}$ K-conversion.

In 1987 and 1988 a lengthy program of improvements to the tritium beta decay apparatus was undertaken.[9] The improvements included the addition of a getter pump to the Kr recirculation loop to remove atmospheric gases, baffling the spectrometer to improve the line shape, superposition of an axial gradient on the solenoid field to eliminate trapping of electrons, and installation of the Si detector described above. Following this work, it was found that it was no longer possible to explain the shape of the Kr spectrum far from the peak -- there was a long tail extending some 400 eV below the diagram line. It happened that the shape of this tail was very similar to the scattering contribution from N_2 and had been fitted out. Now, with no N_2 present, there was a residual tail that could no longer be fitted.

The immediate concern was that this tail might be a part of the instrumental resolution function, which would have important consequences for the neutrino mass derivation. This seemed unlikely, because electron gun data and the spectrum of thermal electrons from the source accelerated to 19 kV had shown no sign of a tail. A more likely explanation was that the feature was in fact part of the Kr spectrum, a part not given (nor even suggested) by theory. To investigate this possibility, a photoionization experiment on Kr was carried out.

IV. PHOTOIONIZATION SPECTRUM OF Kr

The shakeup and shakeoff structures associated with an ejected inner-shell electron should be the same to first order whether the electron has been ejected by internal conversion or photoionization -- one has merely replaced a virtual photon with a real one. Hence the desired satellite spectrum can be measured by photoionization.

Intense beams of synchrotron light in the energy range 10-20 keV are available at the Stanford Synchrotron Radiation Laboratory (SSRL) from the PEP storage ring.[16] A monochromatic beam, prepared by Bragg reflection through a pair of Si(111) crystals, illuminated a Kr gas-jet target. Photoelectrons were analyzed in a double cylindrical mirror analyzer (CMA) equipped with a stage of pre-retardation.[17] Experiments[18] were carried out at two incident photon energies, 15225 and 17025 eV, chosen to place the 1s line and its correlation satellites at energies clear of Auger lines. The CMA was set to analyze 207-eV electrons, and at that energy had a resolution of about 6 eV FWHM. The total resolution was limited by beam divergence to about 15 and 18 eV at the two energies. Some low-statistics data were also taken at 15225 eV in the 3rd harmonic, Si(333), and had an overall resolution of about 7 eV FWHM.

Scanning the spectrum was accomplished by varying the retarding voltage. As Palmberg[17] has shown, this leads to a variation in the phase-space acceptance of the CMA. The efficiency η is then expected to have a power-law dependence:

$$\eta(E_p, E_k) = \eta_0 (E_p/E_k)^n ,$$

where E_p is the pass energy of the CMA, E_k is the incident electron kinetic energy, and n is an exponent whose magnitude depends on the geometrical details of the beam spot and target density distribution. If the beam and target dimensions are much larger than the acceptance volume of the CMA, one expects[17] a contribution to n of 1/2 for each coordinate, and 1/2 for the energy ratio, bringing n to 2. Both larger and smaller exponents are possible. We measured n by recording the diagram line at fixed incident photon energy for various values of E_p. With 15225-eV incident photons, we found n = 2.0(2), and at 17025 eV, n = 2.5(3). It was apparent that the efficiency did not adhere strictly to a power law, and our method did not take into account the variation in efficiency of the channel electron multiplier with electron energy (which spanned the range 452 to 520 eV at the multiplier). The quoted uncertainties include our estimates for these contributions.

Count rates at the photopeak were of order 100 to 300 s^{-1} in the (111) reflection, and 30 s^{-1} in (333). Backgrounds were measured by lowering the photon energy to place the diagram line just below the region of interest. Auger lines block the ranges 0 to 330 eV and 1300 to 2000 eV. A weak continuous background with an intensity 3 x 10^{-5} /eV of the diagram line was found between 330 and 1300 eV. Above 2000 eV there was essentially no background (less than 5 x 10^{-6} /eV). The intrinsic dark rate of the channel electron multiplier, < 1 /s, was reduced a further two orders of magnitude by using the favorable time structure of the PEP beam, a 1-ns pulse every 2 μs. An offline experiment was carried out to investigate whether there might be a scattering tail associated with an intense line in the CMA. With a photoemissive source placed at the object position in front of the CMA, no scattering tail was observed below the monoenergetic line to a level less than 0.5% integrated over the entire spectrum.

The intrinsic lineshape of the monochromatized synchrotron light beam is in principle calculable and can also be derived with some minimal input information about a photoionization spectrum. However, the simplest comparison one can make is to convolve the measured photoionization spectrum (FWHM 18 eV) with a Gaussian having a width adjusted to match the slightly worse resolution (FWHM 26 eV) of the conversion-line data. Such a procedure is certainly adequate to establish whether or not the continuum features of both spectra are the same. The comparison, shown in Fig. 2, reveals that they are indeed the same to a high degree, confirming that the unexpected continuum observed in internal conversion is associated with atomic effects in the Kr atom. Figure 3 shows a comparison between the prediction described above and the high-resolution data from SSRL. Again, the prediction has been convolved with a Gaussian to match the observed resolution. The positions and intensities of the satellites near the diagram line agree remarkably well with the data, obtained

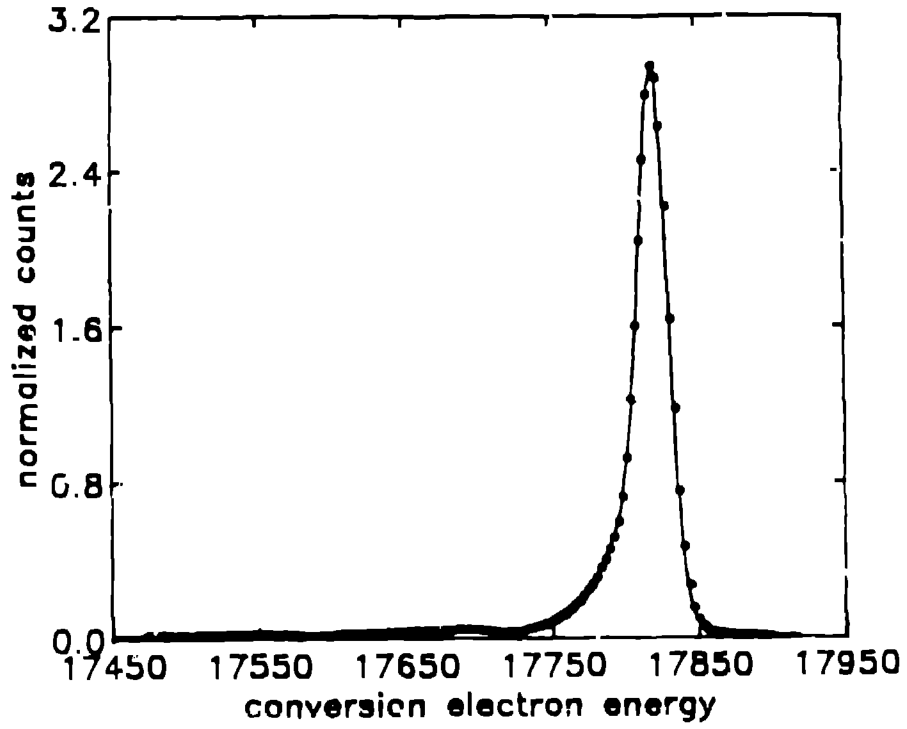

Fig. 2. Comparison between electron spectra from 1s photoionization of Kr (line) and internal conversion (points).

post facto, but the continuum further from the peak is not given by the calculation. The assumption made in the 1987 analysis of the beta spectrum that the instrumental response function had no long tails is qualitatively confirmed.

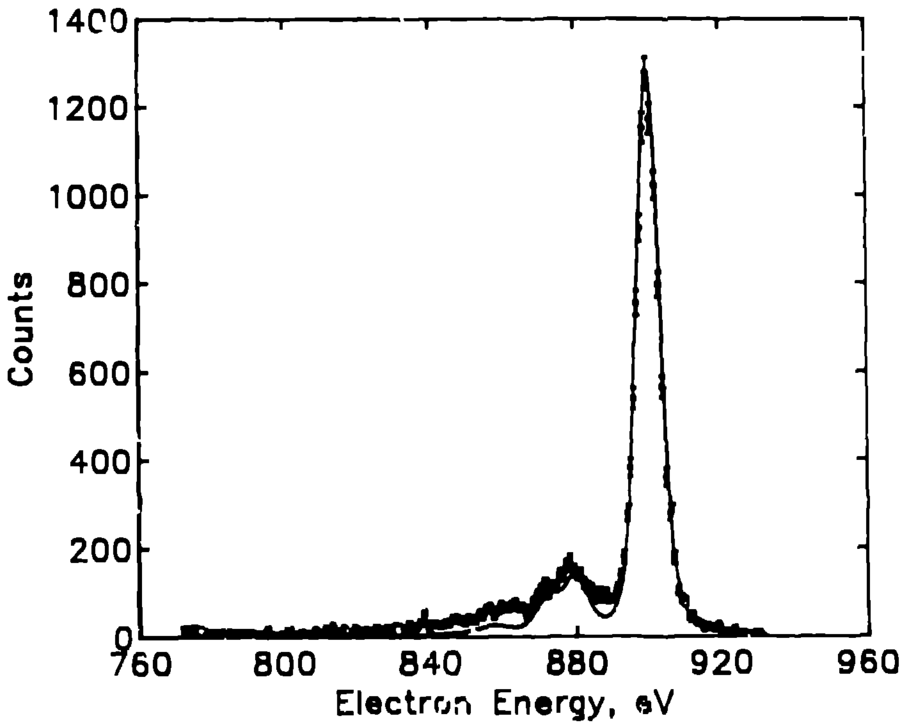

Fig. 3. Comparison between calculated electron spectrum for 1s photoionization of Kr (line) and data (points).

At present we do not know the origin of this continuum feature, but we note that a very similar feature has been seen in 1s photoionization of Ne, and that it interferes coherently with discrete shakeup structure.[19] We speculate that it arises from the direct collision of the ejected 1s electron with an orbital electron in the same atom. That process is indistinguishable in the final state from the usual shakeup and shakeoff one, and would therefore be coherent with it.

V. CONCLUSIONS

The planned improvements to the Los Alamos tritium beta decay apparatus have now been completed. Satisfactory performance of the new multielement Si detector array for the spectrometer has led to increased data rates and better momentum resolution. It is expected that the goal of a neutrino mass sensitiviy of 10 eV will be reached. Studies of the photoionization spectrum of Kr with synchrotron light show a line shape identical to that observed in internal conversion. The long tail observed on this line is found not to be a part of the instrumental response function, but is instead associated with atomic processes in Kr that are at present not theoretically understood.

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